HERMETIC PACKAGES AND FEEDTHROUGHS FOR NEURAL PROSTHESES

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SUMMARY

During the past quarter, we continued testing the wireless humidity monitoring system and monitored the hermeticity of these packages in animal hosts. We continued to monitor, test, and develop the integrated humidity monitoring system, developed alternative methods for biocompatible packaging, and optimized the transmitter for transmitting adequate power to the FINESS chip.

Four glass-silicon packages have been soaking on PBS at room temperatures. As of the end of this quarter, all these packages are still intact and the longest package has been soaking for a total of 2040 days. These packages will continue their soak test until failure is detected.

A wireless system that consists of a hybrid coil and a polyimide relative humidity sensor has been developed. We have packaged a wireless system and soaked in high temperature saline and after 15 months in saline at 97°C, the humidity monitoring system is functional and the package is still dry (confirmed with visual inspection). Six glass-silicon packages with HMS systems have been implanted into various locations in two guinea pigs and after 14 months they all indicate that the packages are hermetic and intact.

Automated tests have been initiated using glass-silicon hermetically sealed packages with enclosed HMS devices. These packages will be monitored to determine the MTTF of the glass silicon packages. An accurate model for the FI-HMS system continues to be developed. New test structures and devices are being fabricated to obtain more data from which a better model can be derived.

Significant advances have been made in bio-packaging. We have demonstrated the use of electroplated gold films as a hermetic seal for neural probe circuitry. Furthermore, we have begun work on biocompatible flip-chip design by investigating solder bonding for interconnections. We have demonstrated improved solder bonding by using our experiences in eutectic bonds.

In the past quarter, we also tested the FINESS chip. As a first step, we directly powered the chips and probed the stimulation outputs. We plan to continue testing in the current quarter, and move on to remote powering with a Class E transmitter.

I. INTRODUCTION

This project aims at the development of hermetic, biocompatible micropackages and feedthroughs for use in a variety of implantable neural prostheses for sensory and motor handicapped individuals. In addition, it will also develop a telemetry system for monitoring package humidity in unrestrained animals, and of telemetry electronics and packaging for stimulation of peripheral nerves. The primary objectives of the proposed research are: 1) the development and characterization of hermetic packages for miniature, silicon-based, implantable neural prostheses designed to interface with the nervous system for many decades; 2) the development of techniques for providing multiple sealed feedthroughs for the hermetic package; 3) the development of custom-designed packages and systems used in several different chronic stimulation or recording applications in the central or peripheral nervous systems in collaboration and cooperation with groups actively involved in developing such systems; and 4) establishing the functionality and biocompatibility of these custom-designed packages in *in-vivo* applications. Although the proposed research is focused on the development of the package and feedthroughs, it also aims at the development of inductively powered systems that can be used in many implantable recording and stimulation devices in general, and of multichannel microstimulators for functional neuromuscular stimulation, and multichannel recording microprobes for CNS applications in particular.

Our group here at the Center for Integrated Sensors and Circuits at the University of Michigan has been involved in the development of silicon-based multichannel recording and stimulating microprobes for use in the central and peripheral nervous systems. More specifically, during the past three contract periods dealing with the development of a single-channel inductively powered microstimulator, our research and development program has made considerable progress in a number of areas related to the above goals. A hermetic packaging technique based on electrostatic bonding of a custom-made glass capsule and a supporting silicon substrate has been developed and has been shown to be hermetic for a period of at least a few decades in salt water environments. This technique allows the transfer of multiple interconnect leads between electronic circuitry and hybrid components located in the sealed interior of the capsule and electrodes located outside of the capsule. The glass capsule can be fabricated using a variety of materials and can be made to have arbitrary dimensions as small as 1.8mm in diameter. A multiple sealed feedthrough technology has been developed that allows the transfer of electrical signals through polysilicon conductor lines located on a silicon support substrate. Many feedthroughs can be fabricated in a small area. The packaging and feedthrough techniques utilize biocompatible materials and can be integrated with a variety of micromachined silicon structures.

The general requirements of the hermetic packages and feedthroughs to be developed under this project are summarized in Table 1. Under this project we will concentrate our efforts to satisfy these requirements and to achieve the goals outlined above. There are a variety of neural prostheses used in different applications, each having different requirements for the package, the feedthroughs, and the particular system application. The overall goal of the program is to develop a miniature hermetic package that can seal a variety of electronic components such as capacitors and coils, and integrated circuits and sensors (in particular electrodes) used in neural prostheses. Although the applications are different, it is possible to identify a number of common requirements in all of these applications in addition to those requirements listed in Table 1. The packaging and feedthrough technology should be capable of:

1- protecting non-planar electronic components such as capacitors and coils, which typically have large dimensions of about a few millimeters, without damaging them;
2- protecting circuit chips that are either integrated monolithically or attached in a hybrid fashion with the substrate that supports the sensors used in the implant;
3- interfacing with structures that contain either thin-film silicon microelectrodes or conventional microelectrodes that are attached to the structure;

Table 1: General Requirements for Miniature Hermetic Packages and Feedthroughs for Neural Prostheses Applications.

Package Lifetime:
≥ 40 Years in Biological Environments @ 37°C

Packaging Temperature:
≤360°C

Package Volume:
10-100 cubic millimeters

Package Material:
Biocompatible
Transparent to Light
Transparent to RF Signals

Package Technology:
Batch Manufactureable

Package Testability:
Capable of Remote Monitoring
In-Situ Sensors (Humidity & Others)

Feedthroughs:
At Least 12 with ≤125μm Pitch
Compatible with Integrated or Hybrid Microelectrodes
Sealed Against Leakage

Testing Protocols:
In-Vitro Under Accelerated Conditions
In-Vivo in Chronic Recording/Stimulation Applications

We have identified two general categories of packages that need to be developed for implantable neural prostheses. The first deals with those systems that contain large components like capacitors, coils, and perhaps hybrid integrated circuit chips. The second deals with those systems that contain only integrated circuit chips that are either integrated in the substrate or are attached in a hybrid fashion to the system.

Figure 1 shows our general proposed approach for the package required in the first category. This figure shows top and cross-sectional views of our proposed approach here. The package is a glass capsule that is electrostatically sealed to a support silicon substrate. Inside the glass capsule are housed all of the necessary components for the system. The electronic circuitry needed for any analog or digital circuit functions is either fabricated on a separate circuit chip that is hybrid mounted on the silicon substrate and electrically connected to the silicon substrate, or integrated monolithically in the support silicon substrate itself. The attachment of the hybrid IC chip to the silicon substrate can be performed using a number of different technologies such as simple wire bonding between pads located on each substrate, or using more sophisticated techniques such as flip-chip solder reflow or tab bonding. The larger capacitor or microcoil components are mounted on either the substrate or the IC chip using appropriate epoxies or solders. This completes the assembly of the electronic components of the system and it should be possible to test the system electronically at this point before the package is completed. After testing, the system is packaged by placing the glass capsule over the entire system and bonding it to the silicon substrate using an electrostatic sealing process. The cavity inside the glass package is now hermetically sealed against the outside environment. Feedthroughs to the outside world are provided using the grid-feedthrough technique discussed in previous reports. These feedthroughs transfer the electrical signals between the electronics inside the package and various elements outside of the package. If the package has to interface with conventional microelectrodes, these microelectrodes can be attached to bonding pads located outside of the package; the bond junctions will have to be protected from the external environment using various polymeric encapsulants. If the package has to interface with on-chip electrodes, it can do so by integrating the electrode on the silicon support substrate. Interconnection is simply achieved using on-chip polysilicon conductors that make the feedthroughs themselves. If the package has to interface with remotely located recording or stimulating electrodes that are attached to the package using a silicon ribbon cable, it can do so by integrating the cable and the electrodes again with the silicon support substrate that houses the package and the electronic components within it.

Figure 2 shows our proposed approach to package development for the second category of applications. In these applications, there are no large components such as capacitors and coils. The only component that needs to be hermetically protected is the electronic circuitry. This circuitry is either monolithically fabricated in the silicon substrate that supports the electrodes (similar to the active multichannel probes being developed by the Michigan group), or is hybrid attached to the silicon substrate that supports the electrodes (like the passive probes being developed by the Michigan group). In both of these cases the package is again another glass capsule that is electrostatically sealed to the silicon substrate. Notice that in this case, the glass package need not be a high profile capsule, but rather it need only have a cavity that is deep enough to allow for the silicon chip to reside within it. Note that although the silicon IC chip is originally 500μm thick, it can be thinned down to about 100μm, or can be recessed in a cavity created in the silicon substrate itself. In either case, the recess in the glass is less than 100μm deep (as opposed to several millimeters for the glass capsule). Such a glass package can be easily fabricated in a batch process from a larger glass wafer.

The above two approaches address the needs for most implantable neural prostheses. Note that both of these techniques utilize a silicon substrate as the supporting base, and are not directly applicable to structures that use other materials such as ceramics or metals. Although this may seem a limitation at first, we believe that the use of silicon is, in fact, an advantage because it is biocompatible and many emerging systems use silicon as a support substrate.

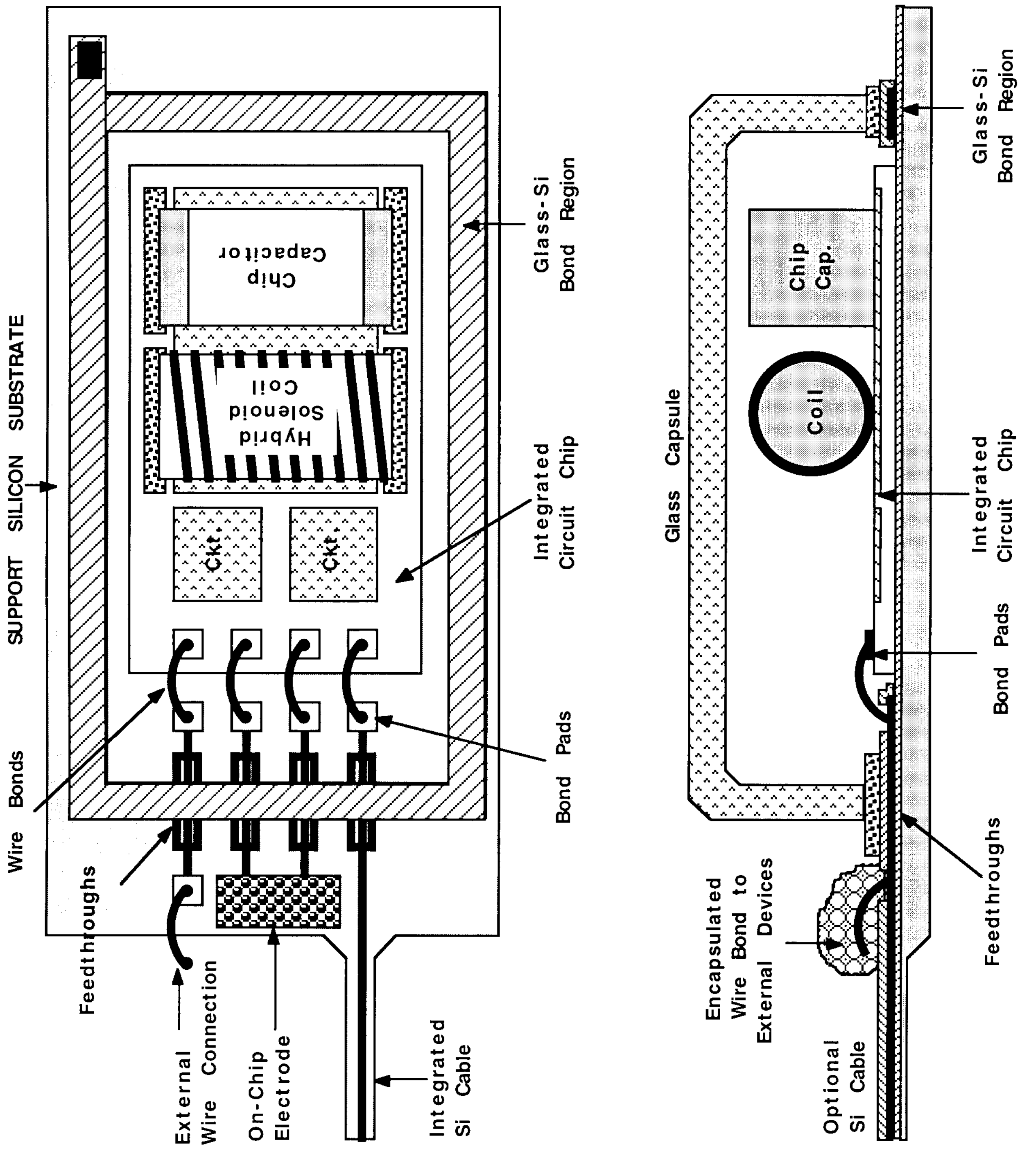


Figure 1: A generic approach for packaging implantable neural prostheses that contain a variety of components such as chip capacitors, microcoils, and integrated circuit chips. This packaging approach allows for connecting to a variety of electrodes.

We will further improve the silicon glass package and its built-in feedthroughs, and will study and explore alternative technologies for hermetic packaging of implantable systems. In particular, we have proposed using a silicon capsule that can be electrostatically bonded to a silicon substrate thus allowing the capsule to be machined down to dimensions below a 100μm. We will also develop an implantable telemetry system for monitoring package humidity in unrestrained animals for a period of at least one year. Two separate systems have been proposed, one based on a simple oscillator, and the other based on a switched-capacitor readout interface circuit and an on-chip low-power AD converter, both using a polyimide-based humidity sensor. This second system will telemeter the humidity information to an outside receiver using a 300MHz on-chip transmitter.

Finally, we have forged potential collaborations with two groups working in the development of recording/stimulating systems for neural prostheses. The first group is that led by Professor Ken Wise at the University of Michigan, which has been involved in the development of miniature, silicon-based multichannel recording and stimulation system for the CNS for many years. Through this collaboration we intend to develop hermetic packages and feedthroughs for a 3-D recording/stimulation system that is under development at Michigan. We will also develop the telemetry front end necessary to deliver power and data to this system. The second group is at Case Western Reserve University, led by Prof. D. Durand, and has been involved in recording and stimulation from peripheral nerves using cuff electrodes. Through this collaboration we intend to develop a fully integrated, low profile, multichannel, hermetic, wireless peripheral nerve stimulator that can be used with their nerve cuff electrode. This system can be directly used with other nerve cuffs that a number of other groups around the country have developed. Both of these collaborations should provide us with significant data on the reliability and biocompatibility of the package.

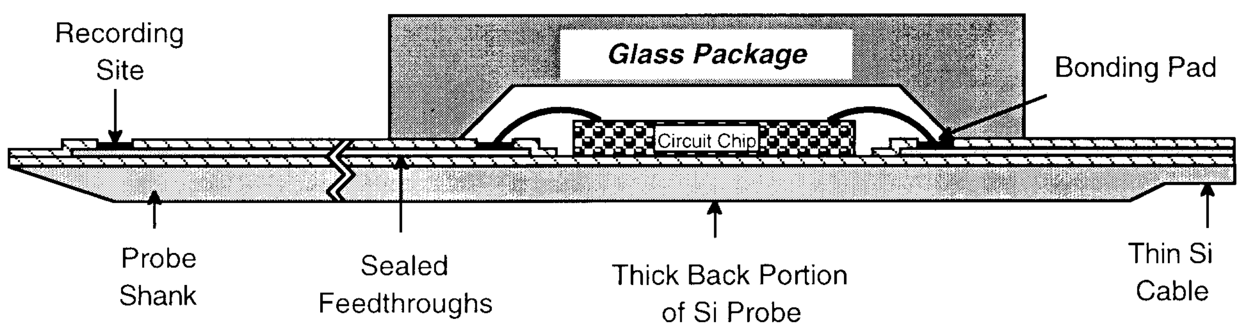


Figure 2: Proposed packaging approach for implantable neural prostheses that contain electronic circuitry, either monolithically fabricated in the probe substrate or hybrid attached to the silicon substrate containing microelectrodes.

II. ACTIVITIES DURING THE PAST QUARTER

2.1 Hermetic Packaging

Over the past few years we have developed a biocompatible hermetic package with high density multiple feedthroughs. This technology utilizes electrostatic bonding of a custom-made glass capsule to a silicon substrate to form a hermetically sealed cavity, as shown in Figure 3. Feedthrough lines are obtained by forming closely spaced polysilicon lines and planarizing them with LTO and PSG. The PSG is reflowed in steam at 1100°C for 2 hours to form a planarized surface. A passivation layer of oxide/nitride/oxide is then deposited on top to prevent direct exposure of PSG to moisture. A layer of fine-grain polysilicon (surface roughness 50Å rms) is deposited and doped to act as the bonding surface. Finally, a glass capsule is bonded to this top polysilicon layer by applying a voltage of 2000V between the two for 12 minutes at 320 to 350°C, a temperature compatible with most hybrid components. The glass capsule can be either custom molded from Corning code #7740 glass, or can be batch fabricated using ultrasonic micromachining of #7740 glass wafers.

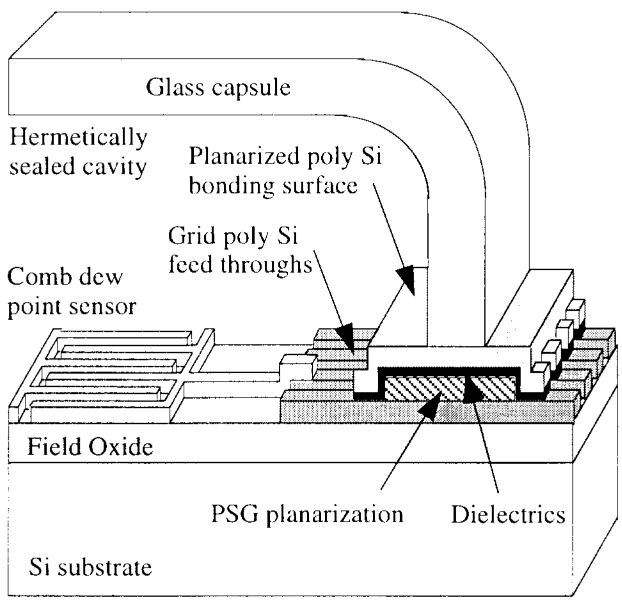


Figure 3: The structure of the hermetic package with grid feedthroughs.

During the past few years we have electrostatically bonded and soak tested over one hundred and sixty of these packages. The bonding yield is about 82% (yield is defined as the percentage of packages which last more than 24 hours in the solution they are soaked in). At the beginning of this quarter 4 devices were still being tested in saline at room temperature. These devices have been under test for over 5 years and show no sign of leakage. We should mention that these devices have been made with silicon substrates that are thinned (~150μm) and bonded to the custom molded glass capsules. We have also continued fabrication of silicon substrates and also continued several in-vivo tests using a wireless humidity sensor-hybrid coil system.

2.1.1 Ongoing Room Temperature Soak Tests in Saline

The packages soaked in phosphate buffered saline at room temperature have been under test for over 5 years. These soak tests were started to complement the accelerated soak tests at the higher temperatures. Furthermore, upon close inspection of the top polysilicon layer, it is found that this top layer is there and is not etched after nearly 5 years of testing. Our conclusion is that at room temperature we are below the activation energy required to cause dissolution of polysilicon and hence we have not yet observed any dissolution related failures. This observation is in accordance with the acceleration model used in interpreting the high temperature tests. Indeed, it seems to confirm that the activation energy for the dissolution of the substrate or the top polysilicon is high. Accordingly, due to the exponential decrease of the acceleration factor with temperature, the dissolution of silicon or polysilicon may not be significant at the body temperature.

Out of the original 6 packages, one failed prematurely the first day and one failed because of mishandling. The 4 other devices are still under test and present no sign of leakage into the capsule after being soaked for 2042 days. Table 2 summarizes the data obtained from these soak tests.

Table 2: Data for room temperature soak tests in saline.

Number of packages in this study	6
Soaking solution	Saline
Failed within 24 hours (not included in MTTF)	1
Packages lost due to mishandling	1
Longest lasting packages in this study	2042 days
Packages still under tests with no measurable room temperature condensation inside	4
Average lifetime to date (MTTF) so far including losses due to mishandling	1659 days
Average lifetime to date (MTTF) so far excluding losses due to mishandling	2033 days

2.2 Wireless Monitoring of Humidity Inside Glass-Silicon Packages

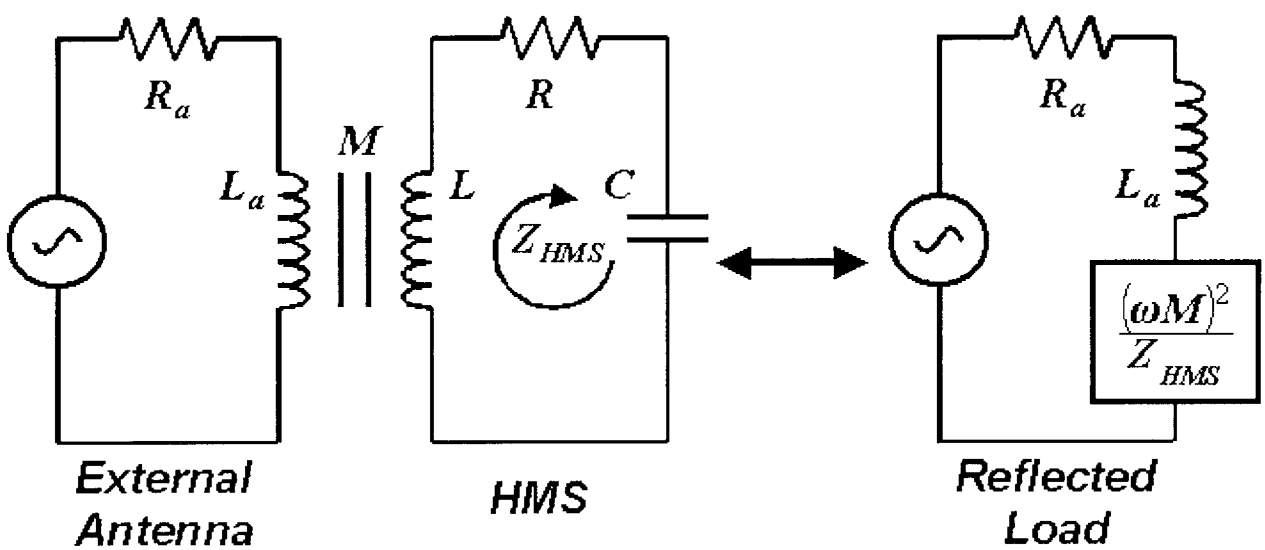
A wireless humidity monitoring system (HMS) has several benefits. First, it greatly facilitates the in-vitro testing of the packages, decreasing the detection threshold of moisture (as compared to dew point sensors used in the room temperature saline tests) and reducing mishandling and temperature cycling. In addition, it would allow one to automate the in-vitro testing procedure. Another benefit is that it allows continuous monitoring of humidity in packages that are implanted in animal hosts, thus providing important in-vivo hermeticity data.

In the previous quarterly reports, the wireless humidity monitoring approach was explained, which can be summarized as the following: a capacitive polyimide humidity sensor (HS) is wire bonded to an inductor made by copper wires wound around a ferrite core. This coil with the HS forms a LC tank circuit. The capacitive humidity sensor in this tank circuit responds to changes in humidity by changing its capacitance and thus the resonance frequency of the tank circuit shifts. When a coil (external antenna) is placed nearby this tank circuit; the maximum loading in the impedance measurements of the antenna is observed at the resonance frequency of the tank circuit allowing one to remotely monitor changes in humidity levels. We thus call the HS and the inductor combination the Humidity Monitoring System (HMS).

2.2.1 System Configuration

The wireless monitoring system consists of an external loop antenna (of inductance L_a), inductively coupled to the humidity monitoring system (HMS). The HMS is a hybrid copper wire coil (with inductance L and series resistance R) wire bonded to a humidity sensor (with capacitance C varying with humidity). The hybrid coil inside the package is modeled as a solenoid (a valid approximation, however, the actual coil has a rectangular shape) and for simplicity, we assume that the antenna coil and the HMS coil are coaxial.

The schematic of the system is given in Figure 4 and the equation nomenclature for this system is given in Table 3.



(a) System configuration (b) Equivalent circuit

Figure 4: The schematic of the humidity monitoring system.

Table 3: Equation nomenclature for the HMS.

Antenna:		Humidity Monitoring System:	
L_a	self-inductance (H)	L	coil self-inductance (H)
a	radius (m)	d	coil diameter (m)
N_a	number of turns	l	coil length (m)
μ_o	permeability (4πe-7 Ohms/m)	S	cross sectional area (m^2)
		$\mu=\mu_o\mu_r$	magnetic permeability
Coupling:		μ_r	relative permeability of the core
M	mutual inductance	C	capacitance of the humidity sensor
Z	axis distance	R	series resistance

Figure 5 shows a HMS used to test the hermeticity of glass-Si anodic bonding. Figure 6 shows the antenna testing setup with a half diced glass capsule revealing the HMS inside.

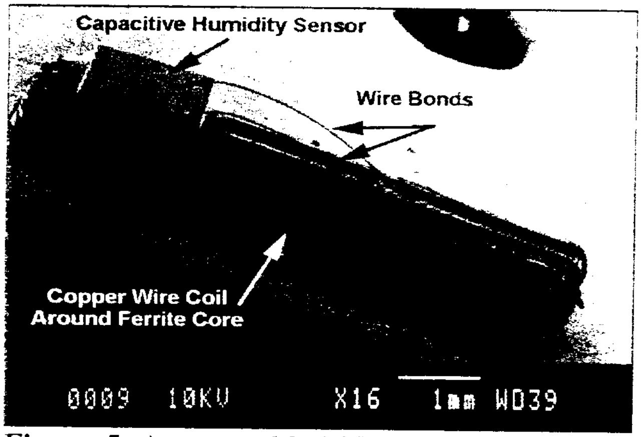


Figure 5: An assembled HMS.

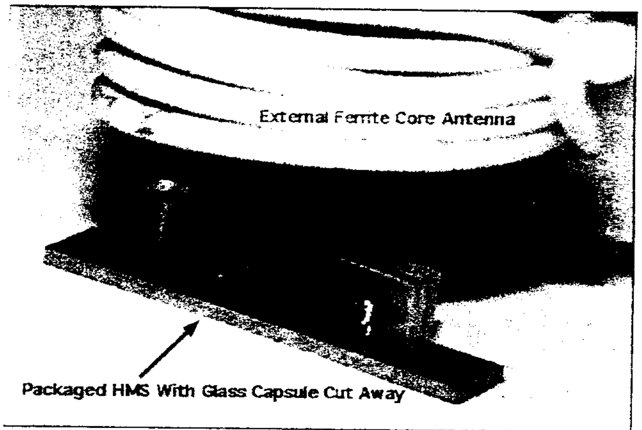


Figure 6: External Antenna and half-diced glass on silicon substrate with enclosed HMS.

A manuscript entitled "A Passive Humidity Monitoring System For In-Situ Remote Wireless Testing Of Micropackages" describing the HMS and wireless telemetry monitoring was submitted to the Journal of Microeletromechanical Systems (JMEMS) for publication.

2.2.2 High Temperature Soak Test in Saline

An anodically-sealed Humidity Monitoring System (HMS) has been soaking since April 1999 in phosphate buffered saline solution at high temperature. The package is inspected routinely under a microscope to detect any leakage path(s) on the bonding surface, and the resonant frequency of the HMS is measured to correlate this response with the humidity inside the sealed package. This data may provide useful information as to the failure and degradation processes of the package hermeticity. As of mid July 2000, neither a complete leakage path nor a corresponding HMS resonant frequency shift has been observed. Figure 7 shows the percent relative humidity change versus the number of days soaking at 97°C.

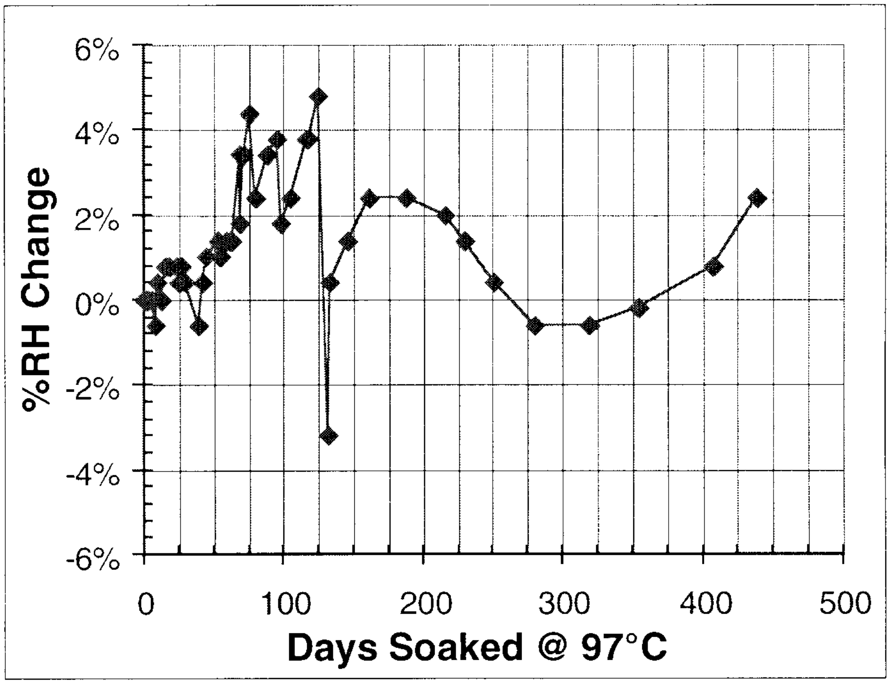


Figure 7: Telemetry data from a package soaked in 97°C saline.

The frequency variations are attributed to day to day temperature fluctuations during testing. These variations are within experimental error and hence the HMS data and visual inspection analysis strongly suggest the anodically sealed package is hermetic for over 1 year.

2.2.3 Automated In-Vitro Testing

The automated test station has been completed and a block diagram of the station is shown in Figure 8.

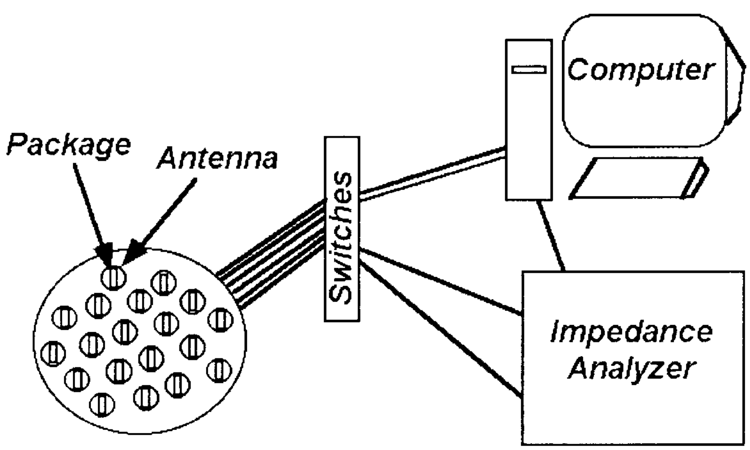


Figure 8: Block diagram of the automated test station.

Ten hermetically sealed glass-silicon packages are placed in phosphate buffered saline solution and set in three ovens: 5 packages at 95°C, 3 packages at 93°C, and 2 packages at 85°C. The bond regions of each package are photographed to monitor any polysilicon etching that may occur. The packages under test have phosphorous doped polysilicon bond regions with gold galvanic bias bond pads. Future tests will include packages with boron doped polysilicon bond regions. In addition, future tests will include new low-profile packages containing FI-HMS systems as shown in Figure 9.

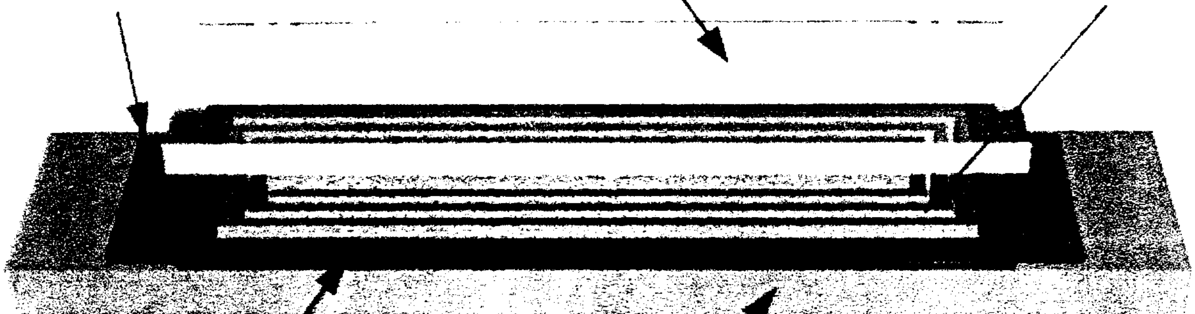


Figure 9: A batch fabricated low-profile package with enclosed FI-HMS.

These devices will be batch fabricated in the coming quarters. The accelerated tests will complement the other saline soak tests and will provide data for calculating the MTTF of the glass-silicon packages.

2.2.4 In-Vivo Testing

With the development of the wireless humidity monitoring system, it is possible to remotely monitor package integrity while the device is implanted in an animal host. Consequently, six devices were prepared and screened to insure hermetic seals. Each device passed a one-day room temperature soak in DI water to validate the seal prior to implant. The devices were then sent to the University of Michigan Medical School for implantation into guinea pig hosts. Two guinea pigs have been implanted with packages to monitor hermeticity in the in-vivo environment. Sites on the guinea pigs were selected to give the widest possible range of environmental conditions. On each host, one package was implanted into the leg, another into the abdomen, and a final one into the head for a total of three packages per host. Devices were implanted in the head beneath the skull but above the dura, under the skin but on top of the leg muscles, and in the abdominal cavity as depicted in Figure 10.

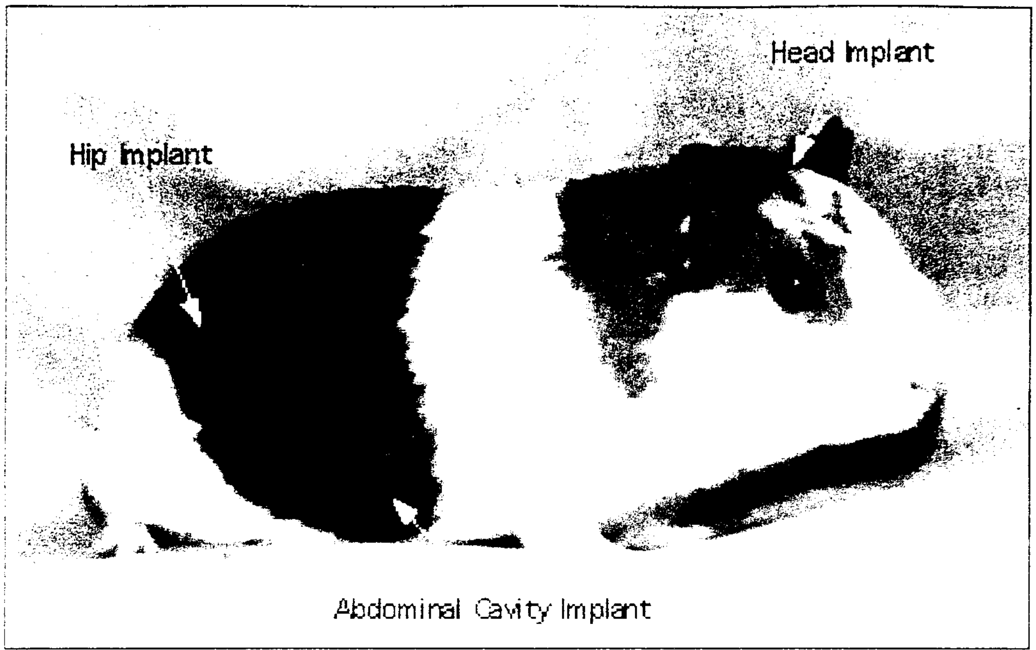


Figure 10: Locations of implanted packages in guinea pig host.

Tests were conducted immediately prior to and following implant, with no discernible change in system output. After this, devices were measured biweekly to detect shifts in resonant frequency resulting from changes of humidity in the package if any. As of July 2000 there has been no discernible shift in the output of any humidity sensing systems inside the packages. Given that a 50 kHz shift is considered significant, the output of the sensors, which varies by only a few kilohertz, indicates fairly steady humidity inside the packages. Figures 11 and 12 show the measured frequencies of the sensors over the duration of the test.

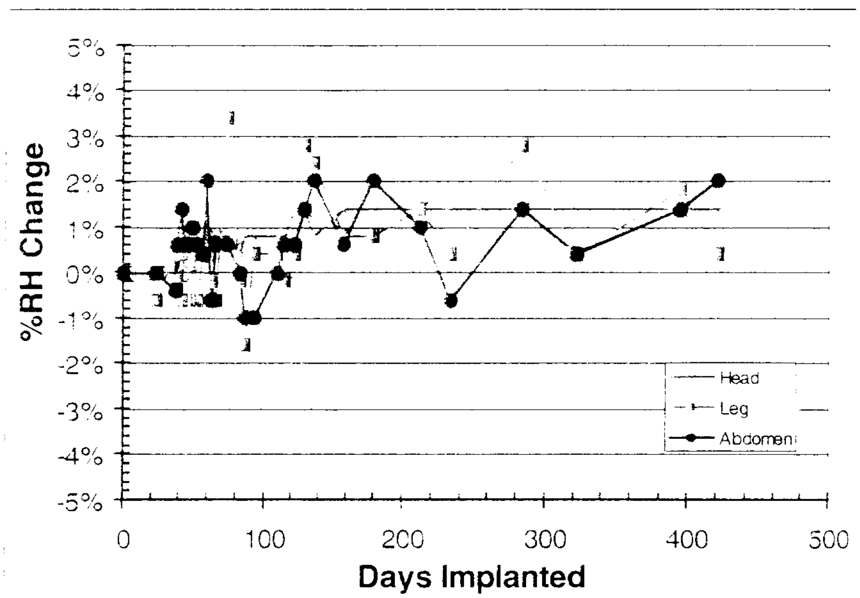


Figure 11: %RH change measurements over time for Guinea Pig A.

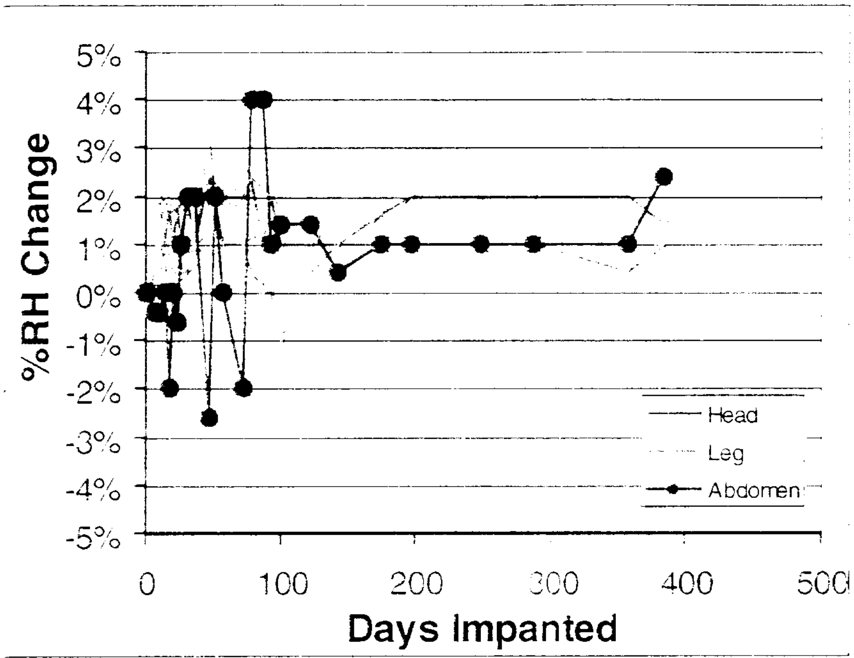


Figure 12: %RH change measurements over time for Guinea Pig B.

We will continue testing the packages in the guinea pigs biweekly and will report further data as it becomes available in the next quarter. The main goal from these tests is to demonstrate that these packages can stay hermetic inside animal hosts.

2.3 A Fully Integrated Humidity Monitoring System

A Fully Integrated Humidity Monitoring System (FI-HMS) is being developed to address the deficiencies of the HMS discussed in the September 1999 NIH report and summarized in Table 4.

Table 4: Deficiencies of the hybrid HMS design

– Tedious time consuming fabrication
– Multiple component system – low yield
– Variation of performance due to hand assembly
– Large device size

The design is shown in Figure 13 and is applicable to the same wireless testing model described in section 2.2.1.

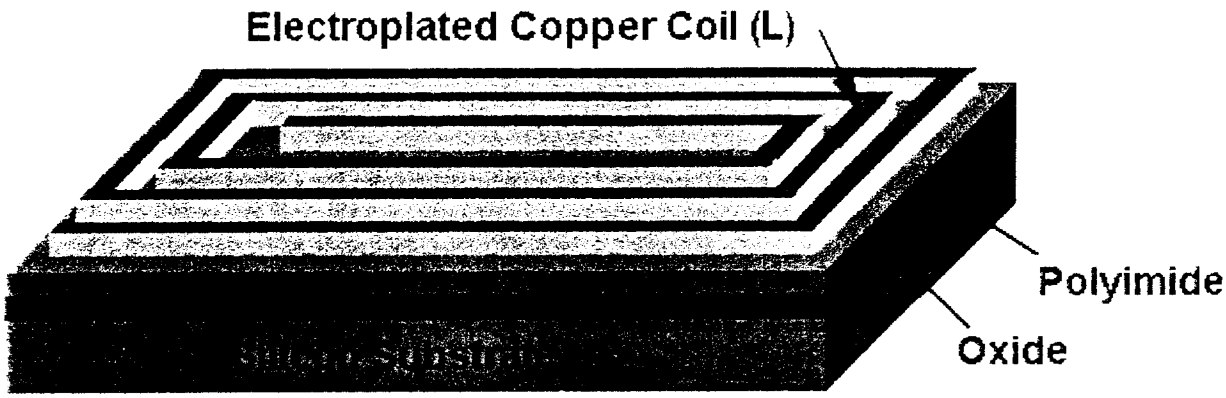


Figure 13: A Fully-Integrated-HMS design.

The equivalent circuit of this design is an LC tank circuit as shown in Figure 4 where the inductor, with inductance L and series resistance R, is the planar copper coil and the capacitor, with capacitance C, is between the copper coil and the conductive silicon substrate separated by dielectrics (in this case – SiO_2 and humidity sensitive polyimide).

2.3.1 FI-HMS Model

The FI-HMS model continues to be developed to accurately describe the inductance, capacitance, and resistance of the device. As previously reported, the capacitance and inductance models needed improvement. The inductance expression has been previously reported with the design of the FINESS chip integrated planar copper coil inductor; whereas, the resistance and capacitance are obtained using the linear length of the entire coil, d_L. The expressions for L [8], R, and C are

$$k1 = L_{eff} \cdot \ln\left(L_{eff} + \sqrt{L_{eff}^2 + W_{eff}^2}\right) \qquad \text{Eq. 1}$$

$$k2 = W_{eff} \cdot \ln\left(W_{eff} + \sqrt{L_{eff}^2 + W_{eff}^2}\right) \qquad \text{Eq. 2}$$

$$L = 9.21 \times 10^{-9} \cdot N^2 \cdot \mu\left[(L_{eff} + W_{eff}) \cdot \ln\left(\frac{8 \cdot L_{eff} \cdot W_{eff}}{N \cdot h + N \cdot w}\right) - k1 - k2\right] \qquad \text{Eq. 3}$$

$$d_L = 2 \cdot N \cdot \left[(L_{coil} + W_{coil}) - 2 \cdot w - 2 \cdot (w + s) \cdot (N - 1)\right] \qquad \text{Eq. 4}$$

$$R = d_L \cdot \frac{\rho}{w \cdot h} \qquad \text{Eq. 5}$$

$$C_{substrate} = d_L \cdot \frac{w \cdot \varepsilon}{t} \qquad \text{Eq. 6}$$

$$C_{interwinding} = \frac{\partial \mathring{a}(d_L - 2(L_{coil} + W_{coil}))}{N \cdot \ln\left(\frac{(w+s)}{h} + \sqrt{\left(\frac{(w+s)}{h}\right)^2 - 1} \right)} \qquad \text{Eq. 7}$$

Note that there are multiple capacitances that are included in this model $C_{substrate}$ and $C_{interwinding}$ [11]. $C_{substrate}$ is the capacitance between the copper coil and the silicon substrate with a polyimide dielectric layer. $C_{interwinding}$ is the capacitance between adjacent windings. The equation nomenclature is provided in Table 5.

Table 5: Equation nomenclature for the FI-HMS.

FI-HMS:	
L_{coil}	length of the coil
W_{coil}	width of the coil
L_{eff}	effective length of the coil
W_{eff}	effective width of the coil
N	number of turns
h	coil height (plating height)
w	width of coil lines
s	spacing between adjacent coils
d_L	mutual inductance
t	dielectric thickness
ρ	resistivity
μ	permeability
ε	permittivity

These equations are used to evaluate data presented in the next section.

2.3.2 FI-HMS Evaluation

The experimental total FI-HMS capacitance is derived from the equation:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad \Rightarrow \quad C = \frac{1}{L \cdot (2\pi f_o)^2}. \qquad \text{Eq. 8}$$

Figure 14 plots the total FI-HMS capacitance (using Eq. 8 for the derivation), Figure 15 shows, $C_{substrate}$, calculated from the data using Eq. 6 and Figure 16 plots the theoretical substrate capacitance, $C_{interwinding}$, calculated using Eq. 7.

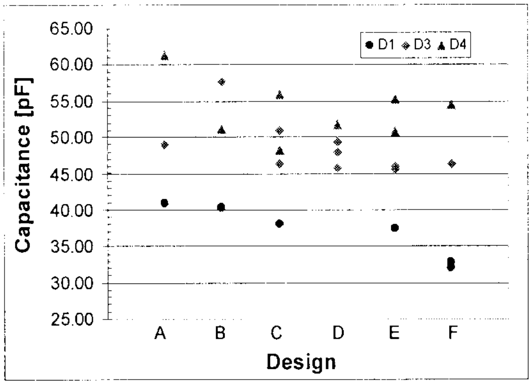


Figure 14: Calculated FI-HMS capacitance from measure L and f_o.

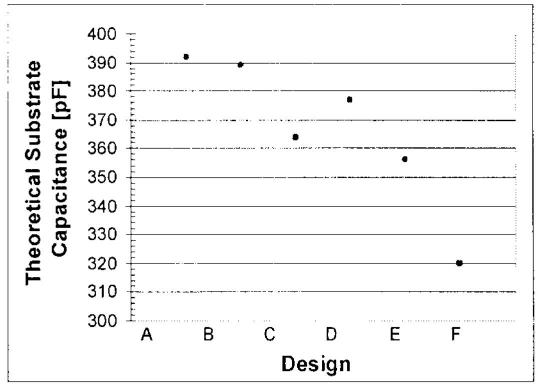


Figure 15: Theoretical Substrate Capacitance, $C_{substrate}$.

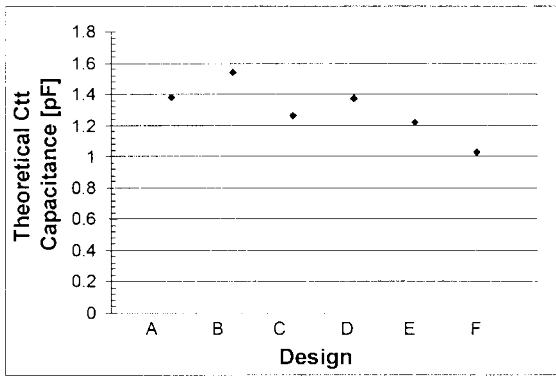


Figure 16: Theoretical Interwinding Capacitance, $C_{interwinding}$.

It is clear that these capacitance models given by Eqs. 6 & 7 do not accurately describe the device capacitance, thus research will continue to develop this model. New test structures and devices are being fabricated to obtain more data from which a better model can be derived.

2.5 Novel Packaging Technologies

In the interest of developing a Si-Si bonding technology for flip chip devices, several novel encapsulation techniques have been investigated. The goal of this research is to find a technology that is biocompatible and can be used to make complicated bioMEMS systems. Current microsystems designed for biological applications are limited by low yield resulting from complicated process flows. By developing a technology that can separate the complexities of circuit design from the complexities of building implantable microsystems, it is possible to greatly simplify the production of implantable biosystems. Critical to this research is to develop a method that makes low temperature hermetic biocompatible encapsulation possible for Si-Si bonding. The long-term goal of this research is to enable the production of devices that are structurally similar to Figure 18.

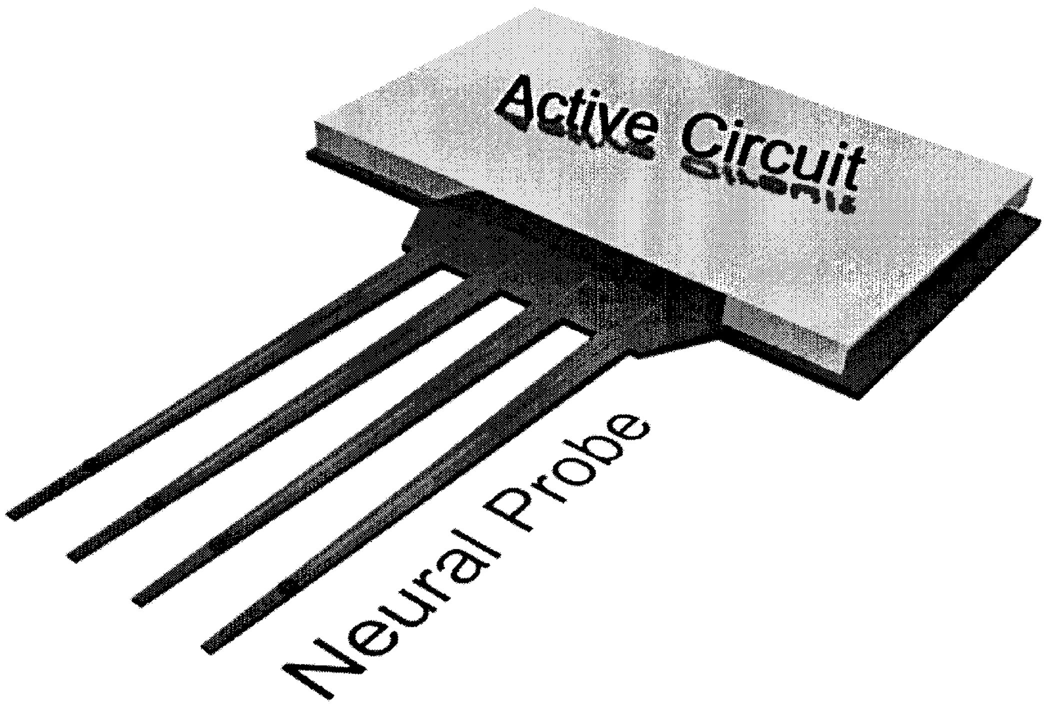


Figure 18: Schematic of our long-term plans for flip chip technology.

2.5.1 Packaging Experiments for Neural Probes

As part of our work on hermetic biocompatible packaging, we would like to extend our technology to devices other than the microstimulator. One obvious potential application of this technology lies in the development of a packaging technology for active neural probes. The active neural probe is designed to record neural signals at multiple sites, but has been heretofore limited to acute implants because there was no adequate package to protect the circuitry for long term implants. As a result, we are adapting our packaging technology to develop a hermetically sealed neural probe for chronic implantation. The most recent research into neural probes has focused upon using electroplated films to seal the probe. A relatively thick film of gold should provide a long-term hermetic seal for the probes. Figure 19 shows the concept of the packaged neural probe.

The initial step in constructing the packaged neural probe is to build a test structure to study the feasibility of wafer level encapsulation. While the technology for building the neural probes is well established, a method for wafer level encapsulation is not. Instead of using expensive active probes to prove the initial efficacy of this encapsulation method, structures utilizing encapsulated polyimide were developed. The process for this test structure is shown in Figure 20 (a-e).

In the EDP release, a hermetically sealed package will protect the underlying polyimide. However, if there is a defect in the seal, the polyimide will dissolve. As a result, a simple cross section of the device after release reveals if there is a hermetic seal. In the past quarter, these test structures were fabricated.

The probes were cross sectioned by removing the silicon from the back of the probes and examined for presence of polyimide. Figure 21 shows a failed probe. It shows the chromium adhesion layer on the probe and the gold electroplated foil. This device failed due to lithographic defects in the phot mask

After adjusting the parameters of the process, the yield was improved and the devices survived the packaging process. Figures 22 a & b show cross sections of surviving probes. The polyimide, which contains trapped bubbles, is clearly visible and looks remarkably distinct from the gold foil.

This shows that electroplated films are capable of encapsulating devices for long-term implants. Given that these devices have already survived a 10 hour EDP release, there is a high probability that they will have a long lifetime inside the body. In the coming quarter, we will fabricate humidity sensors using this structure to test the lifetime of electroplated packaging.

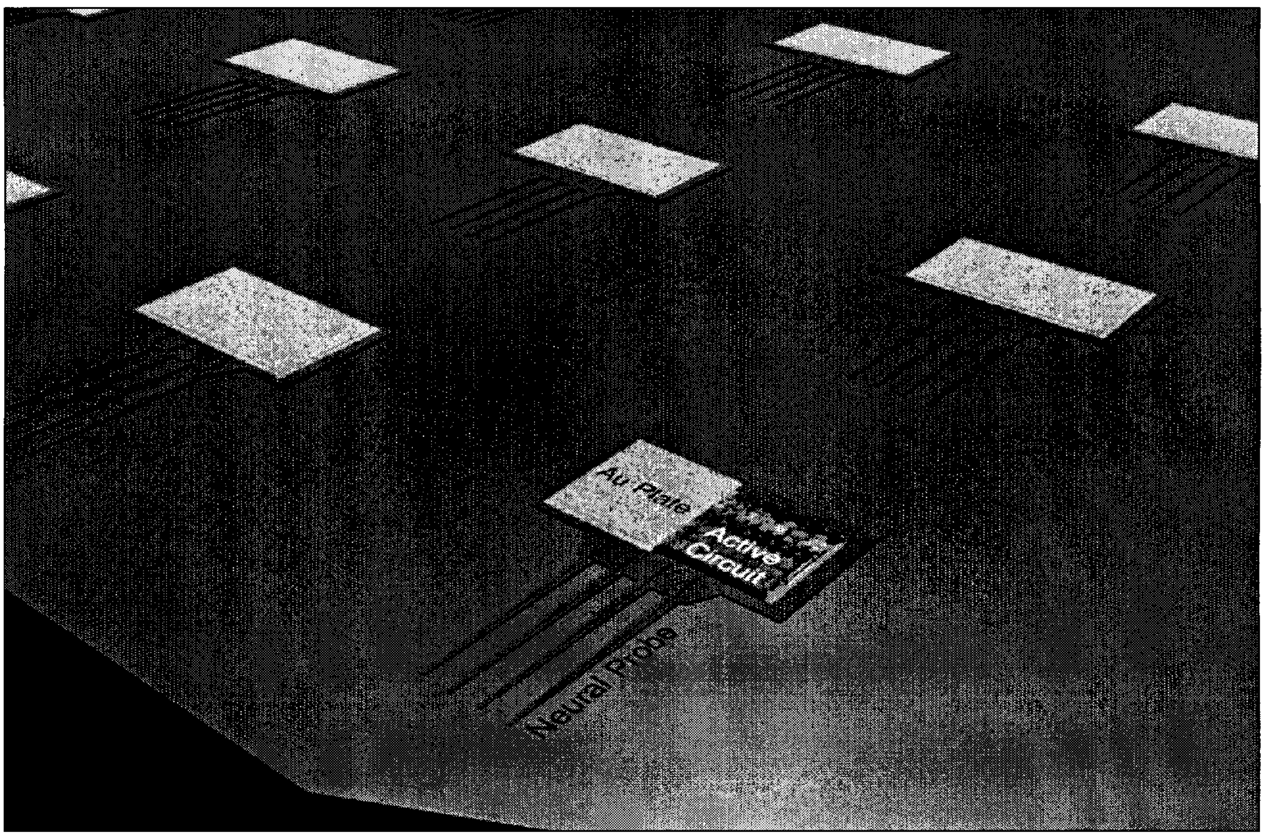
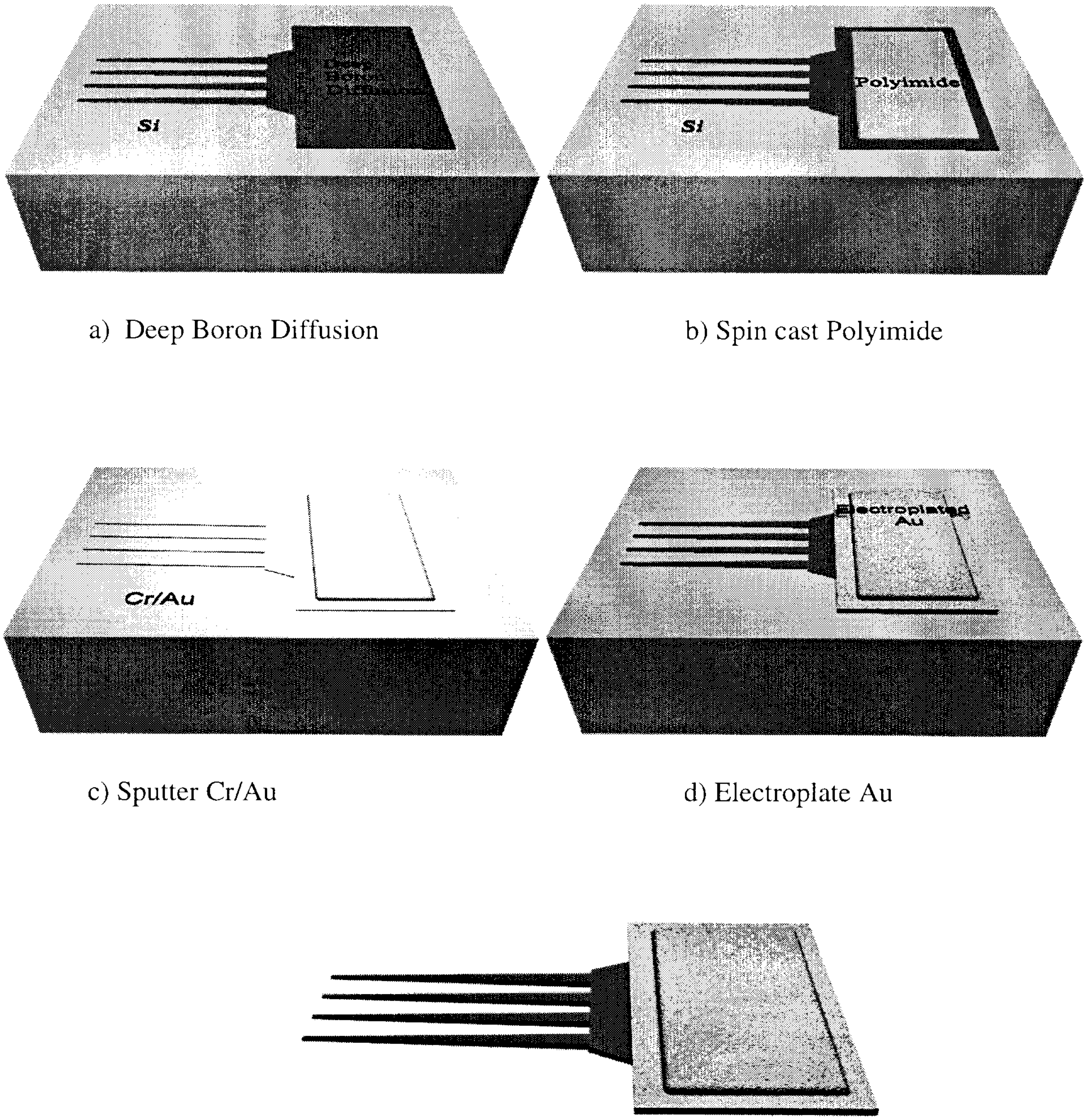


Figure 19: Schematic of packaged neural probe.



a) Deep Boron Diffusion

b) Spin cast Polyimide

c) Sputter Cr/Au

d) Electroplate Au

e) EDP release

Figure 20 (a-e): Process for neural probe test structure.

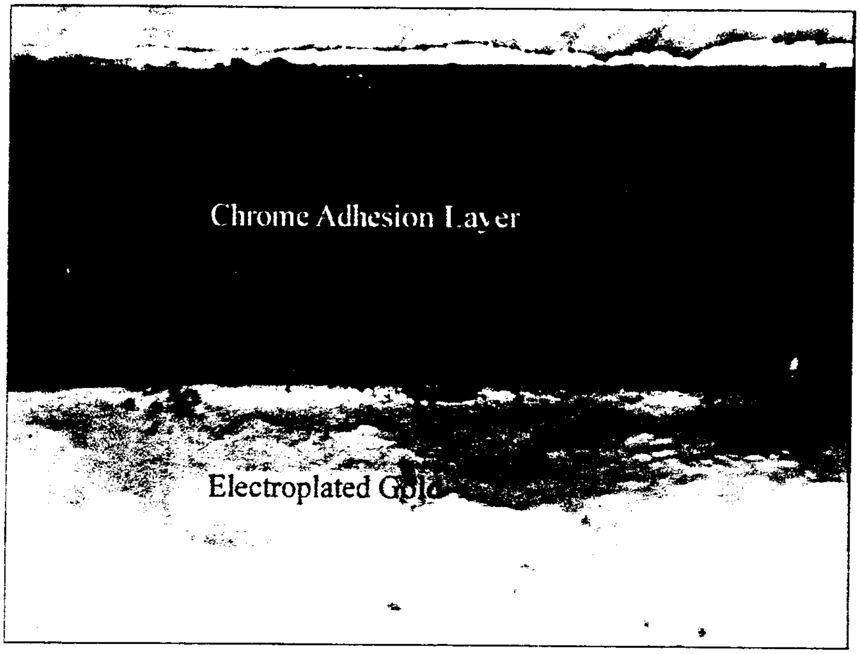


Figure 21: Failed probe packaging viewed from the top after cross section. Note that the dark region is where the electroplated cap touches the silicon probe. We should observe polyimide where there is electroplated gold, but there is none.

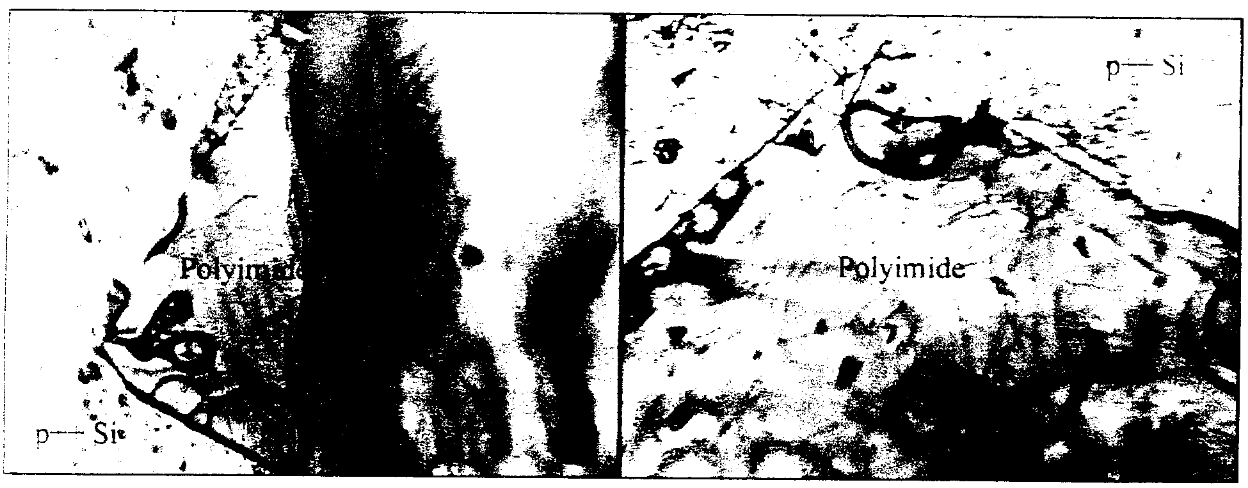


Figure 22 (a, b): Cross section of surviving probes. The polyimide is clearly visible next to the remains of the boron-doped silicon.

2.5.2 Solder for Interconnections

As part of our plans to develop biocompatible flip chip technology for implantable probes and stimulators, we have begun to investigate the use of solders for electrical and mechanical connectors between the circuit and sensor wafers. A schematic of the flip chip approach is shown in Figure 23.

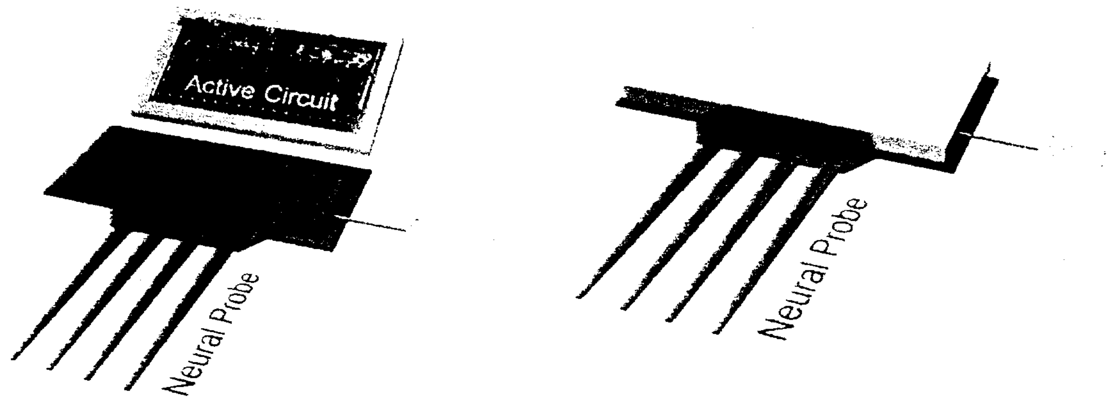


Figure 23: Concept of solder based flip chip probes

The use of solder has been well established in the electronics industry for years. Our research into this area is only to develop a technology for use in future biocompatible flip chips, not to make substantial improvements in soldering technologies. To demonstrate the feasibility of this approach, a test structure was developed. Shown in Figure 24, this structure consists of a broken ring of solder on a Si die. This structure is bonded to a cap die and then broken apart to examine the quality of the bond.

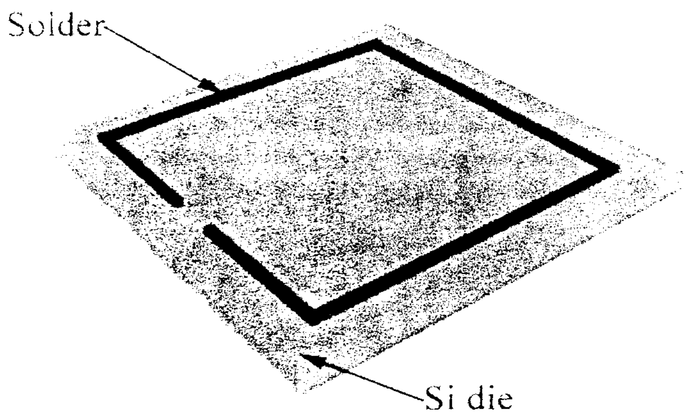


Figure 24: Test structure for solder experiments.

In order to deposit solder onto Si, a commercially available electroplating solution was used that deposits a Pb40Sn60 solder. This film will reflowed at a temperature above 190°C. This solder was deposited with a photoresist mask and showed good uniformity, as shown in Figure 25.

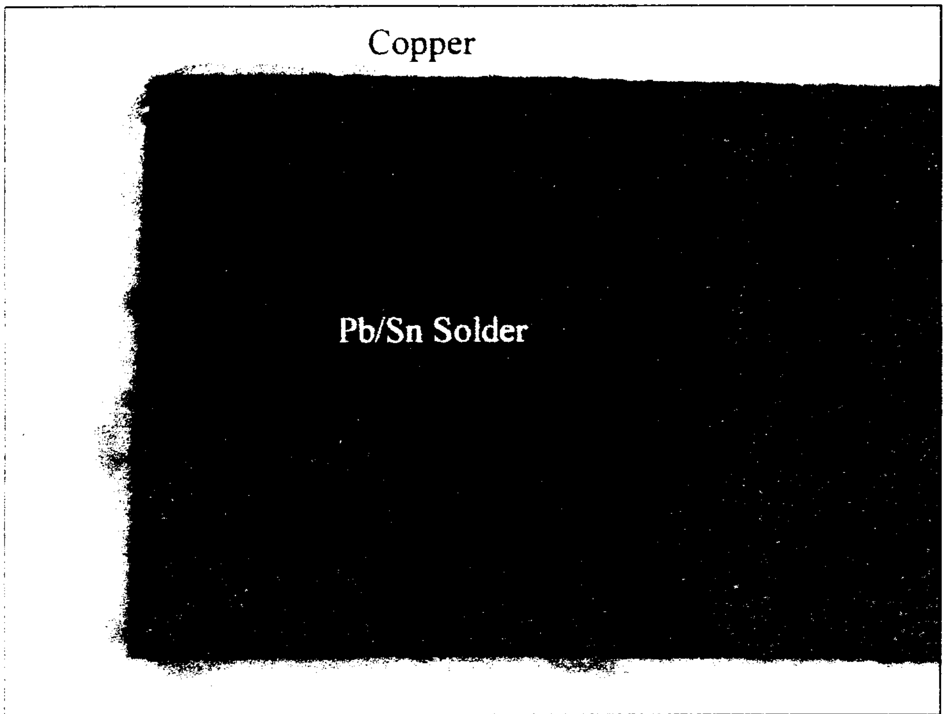


Figure 25: Pb/Sn solder film.

Initial bonding attempts gave sporadic die attachments, as shown in Figure 26 a & b.

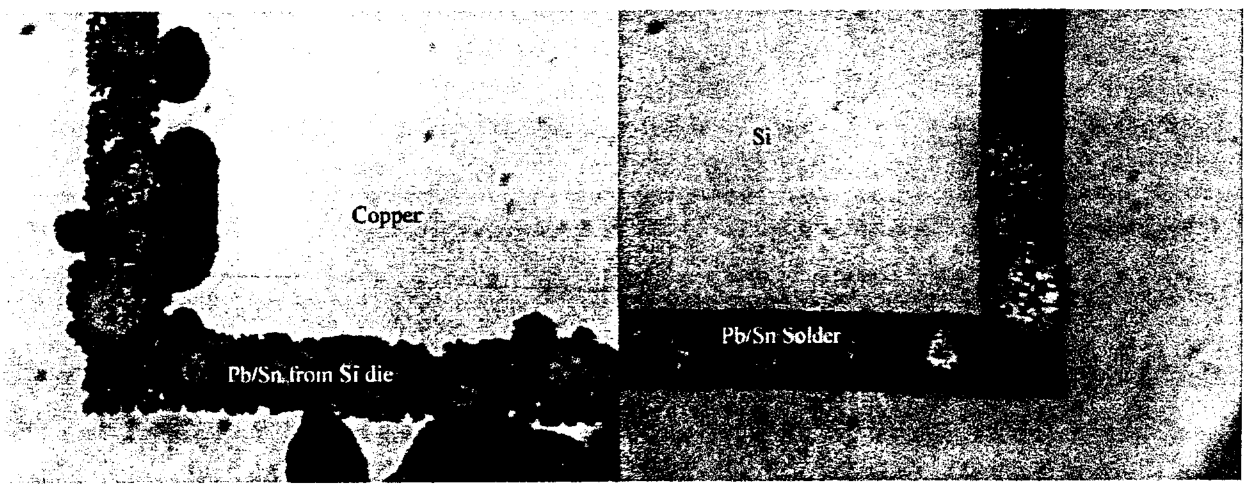


Figure 26 (a, b): Initial bonding attempts showing cap wafer (left) and base wafer (right).

While these bonds were adequate to our needs, a more uniform bond is desired. To achieve this without employing flux or cumbersome fluorine plasma pre-treatments, the bonding process was modified to include multiple reflows, which has been shown in other eutectic systems to improve bond quality. This had a marked effect in the quality of the bond, as shown in Figure 27 a & b.

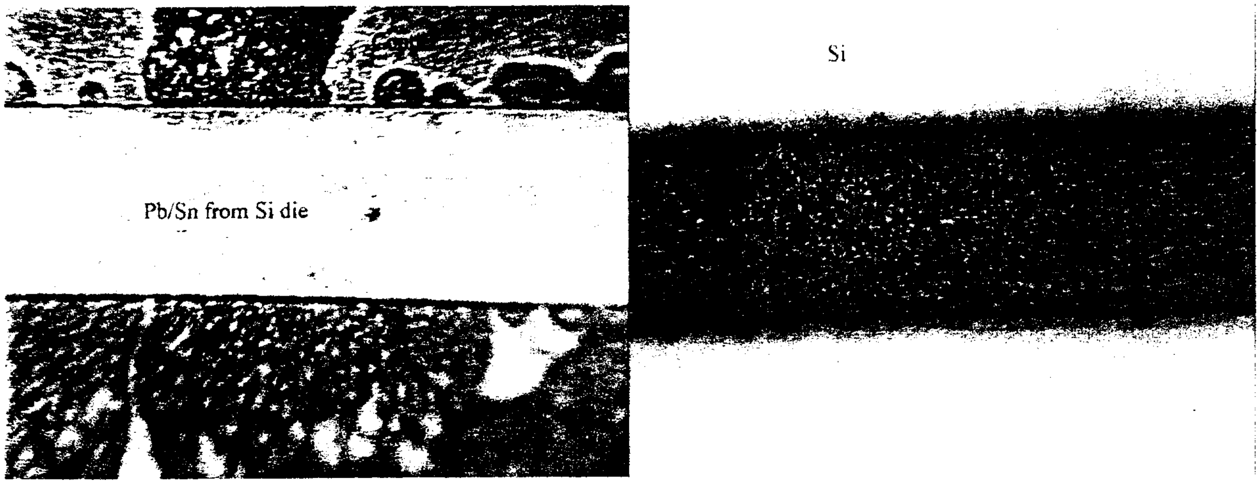


Figure 27 (a, b): Modified bonding process showing improved bonding on cap wafer (left) and base wafer (right).

While there is some obvious diffusion of material into the surrounding copper, this is felt to be a minor concern, since the actual flip chip will have a patterned copper film, which will eliminate the problem of diffusion into surrounding regions. In the coming quarter, we plan to use this technology to demonstrate a biocompatible hermetic flip chip.

III. PLANS FOR THE COMING QUARTER

Further research into thick resist materials and process for increased plating height will continue. FI-HMS devices will be characterized and an accurate model will be developed so that the design can be optimized for sensitivity, testing distance. After testing and characterization of the FI-HMS devices they may be used for humidity monitoring in the glass silicon package. We will continue wireless monitoring the of the implanted and accelerated test packages.

A batch fabricated low profile package will be developed for accelerated testing purposes. The batch-fabricated packages will greatly reduce the throughput time for obtaining hermetically sealed packages for accelerated testing.

In the coming quarter we plan to develop test structures to measure the lifetime of our electroplated gold packages. We also plan to continue our research into solder bonding in order to demonstrate a biocompatible flip chip.

In the coming quarter, we will continue testing the FINESS chips. After ensuring their proper operation, we will move on to remote powering the chips. Once we establish the proper working of the FINESS chip- Class E transmitter system, we will make more chips and interact with our collaborators to use this system in their experimental set-ups to stimulate peripheral nerves *in vivo*.

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